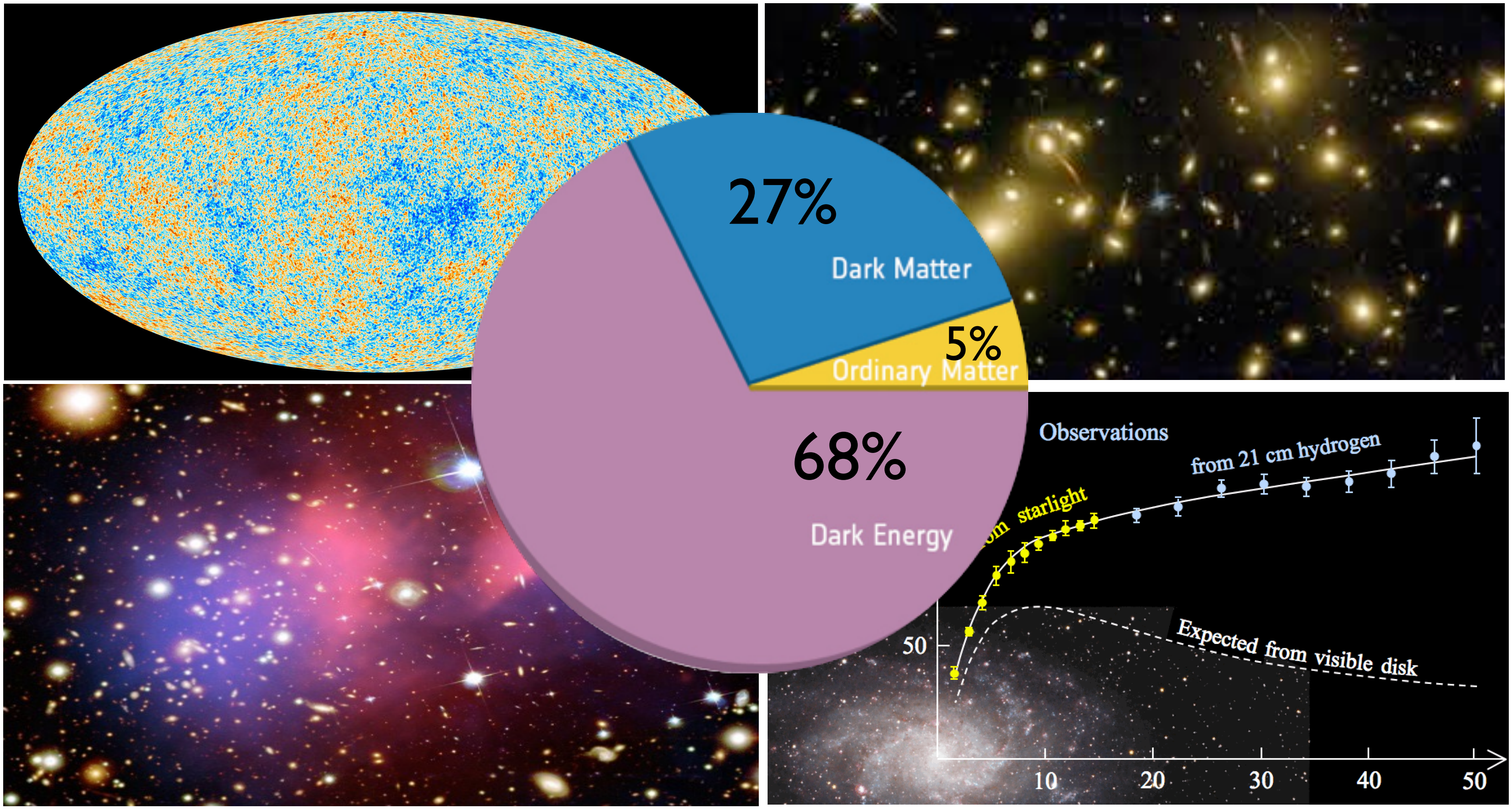
Self-Interacting Dark Matter: Models, Simulations, and Signals

Organizers: Camila Correa, Fabio Iocco, Manoj Kaplinghat, Laura Sagunski, Hai-Bo Yu

Dark Matter


27%
Dark Matter
5%
Ordinary Matter
68%
Dark Energy
Observations
from 21 cm hydrogen
starlight
Expected from visible disk
50
10
20
30
40
50

Terrestrial DM Search Status

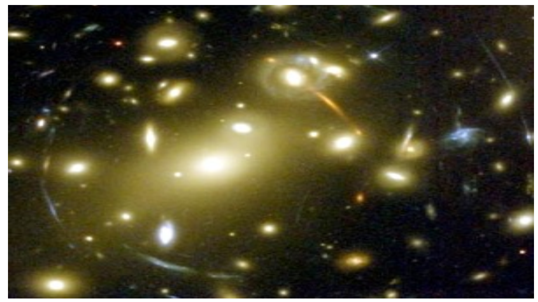
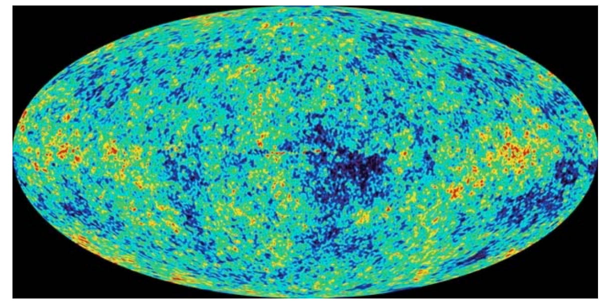
"上穷碧落下黄泉，两处茫茫皆不见。"白居易《长恨歌》

"He exhausted all avenues in heaven and the nether world,
… he could not bring her existence to light."

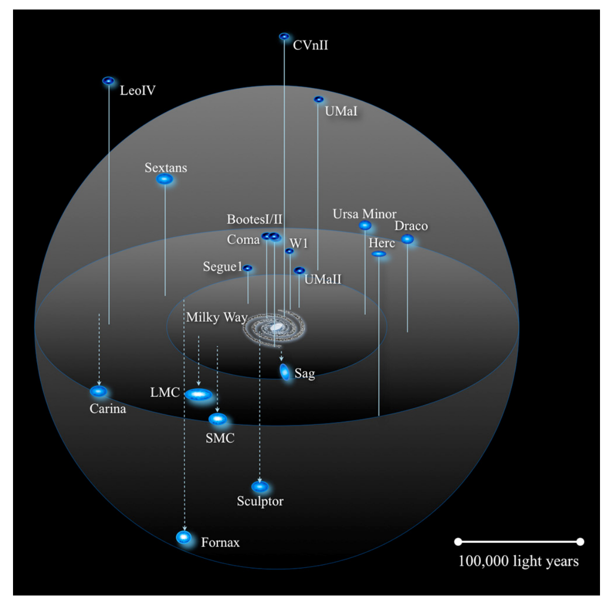
A Song of Immortal Regret, Bai Juyi (772-846)

Cold Dark Matter (CDM)

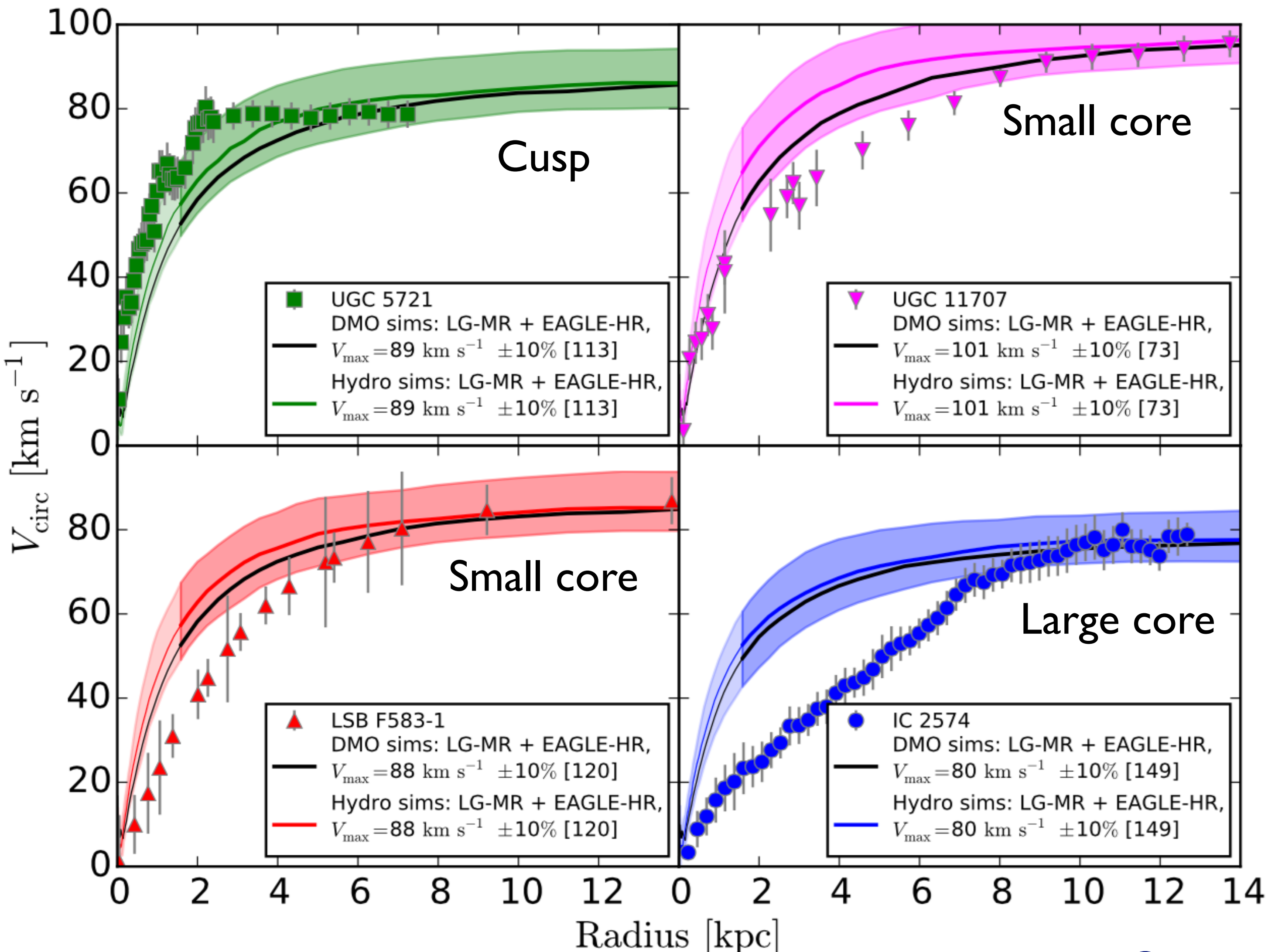
- Large scales: very well

- Small scales (dwarf galaxies, sub-halos, galaxy clusters)
  - Core vs Cusp
  - Diversity
  - Too big to fail
  - Ultra-diffuse galaxies
  - …

The Diversity Problem



All galaxies have the same observed Vmax!

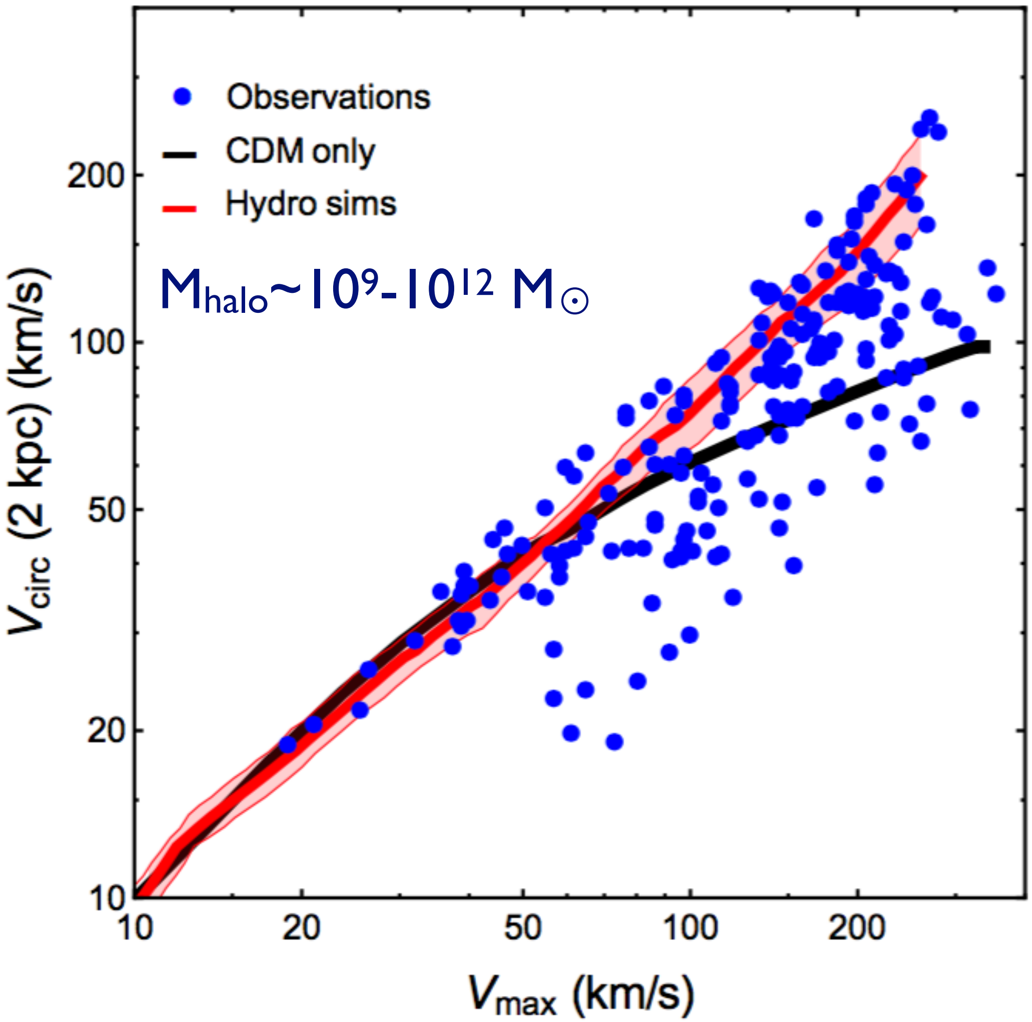
$$V \sim \sqrt{GM/r}$$

Oman+(2015)

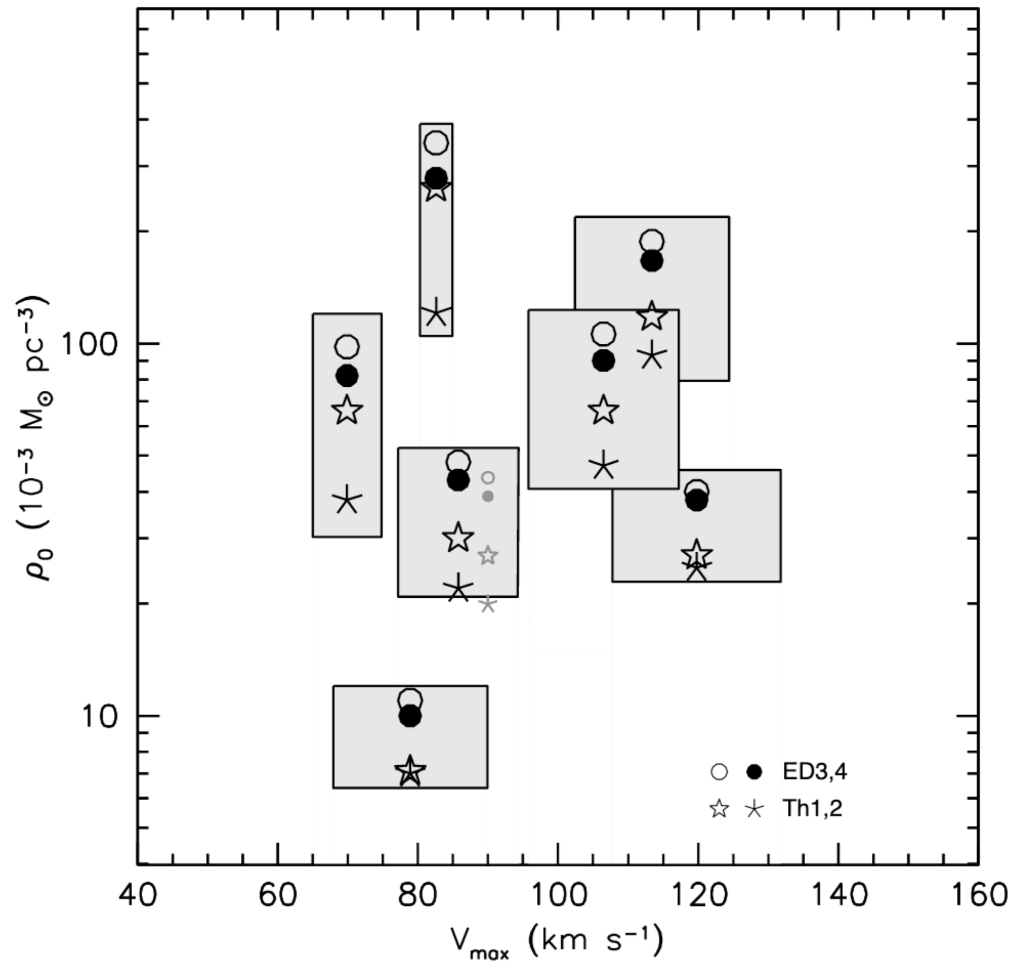
Colored bands: hydrodynamical simulations of CDM

The rotation curves are diverse!

Diversity: A Big Challenge



the data compiled in Oman+(2015)



Kuzio de Naray, Martinez, Bullock, Kaplinghat (2010)

Dark matter distributions are diverse in spiral galaxies

THE CASE AGAINST WARM OR SELF-INTERACTING DARK MATTER AS EXPLANATIONS FOR CORES IN LOW SURFACE BRIGHTNESS GALAXIES

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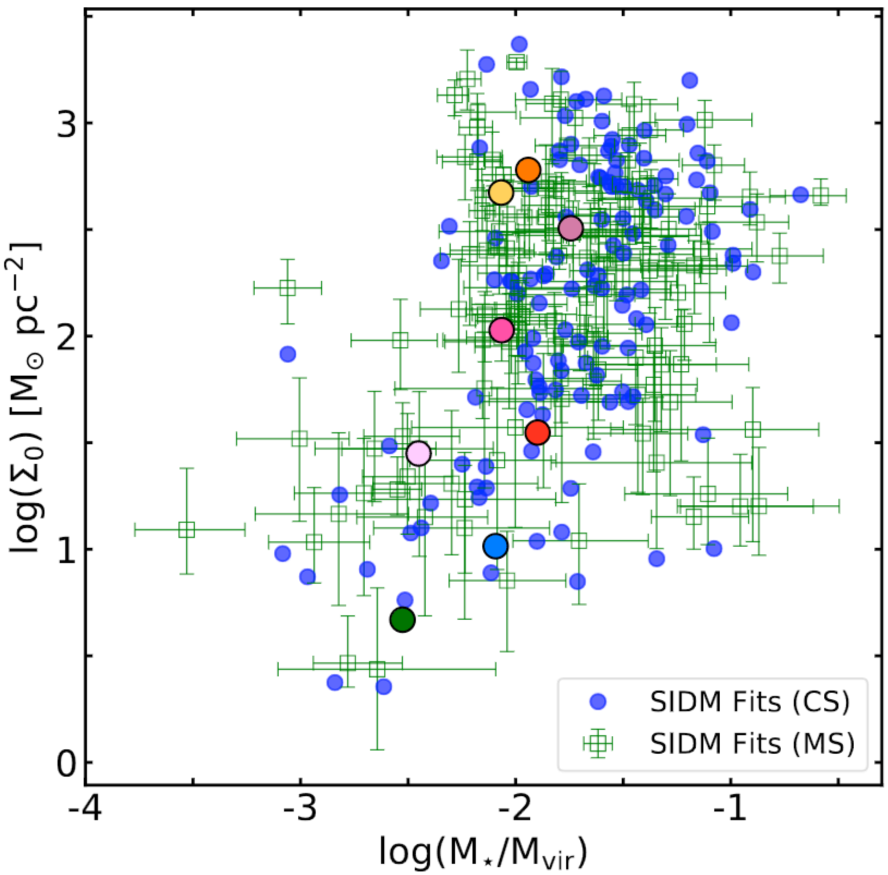
Accepted to ApJL

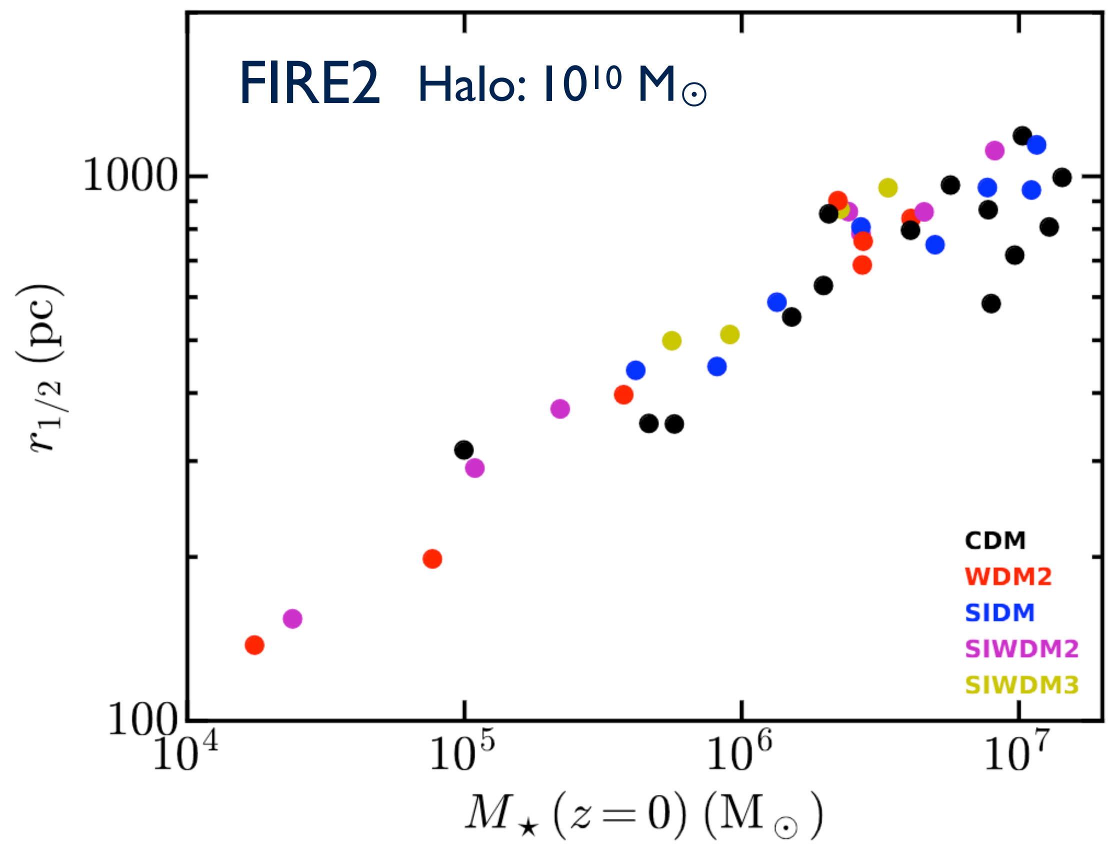
ABSTRACT

Warm dark matter (WDM) and self-interacting dark matter (SIDM) are often motivated by the inferred cores in the dark matter halos of low surface brightness (LSB) galaxies. We test thermal WDM, non-thermal WDM, and SIDM using high-resolution rotation curves of nine LSB galaxies. We fit these dark matter models to the data and determine the halo core radii and central densities. While the minimum core size in WDM models is predicted to decrease with halo mass, we find that the inferred core radii increase with halo mass and also cannot be explained with a single value of the primordial phase space density. Moreover, if the core size is set by WDM particle properties, then even the smallest cores we infer would require primordial phase space density values that are orders of magnitude smaller than lower limits obtained from the Lyman alpha forest power spectra. We also find that the dark matter halo core densities vary by a factor of about 30 from system to system while showing no systematic trend with the maximum rotation velocity of the galaxy. This strongly argues against the core size being directly set by large self-interactions (scattering or annihilation) of dark matter. We therefore conclude that the inferred cores do not provide motivation to prefer WDM or SIDM over other dark matter models.

Subject headings: cosmology: observations — cosmology: theory — dark matter — galaxies: kinematics and dynamics

Diverse Baryon Distributions





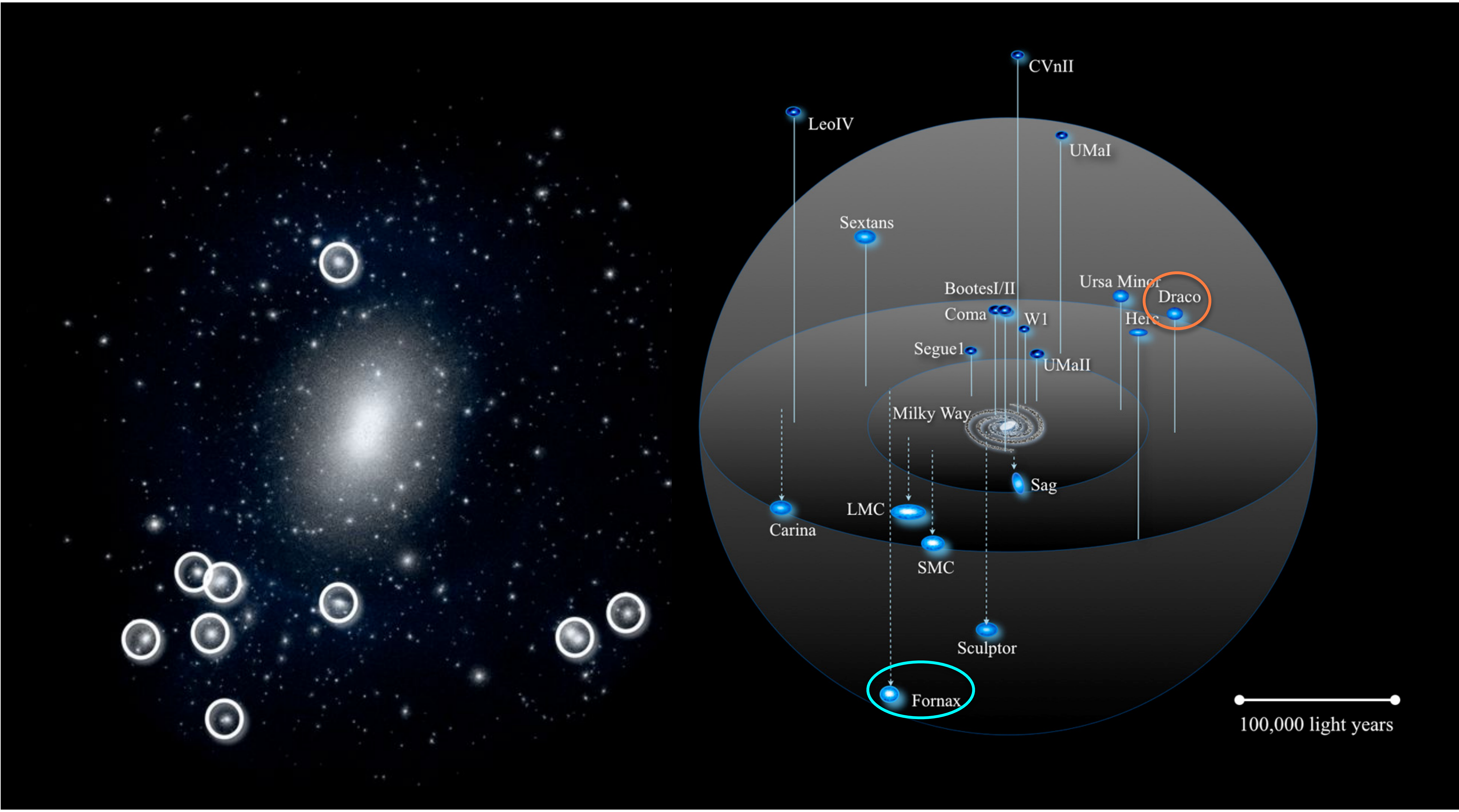
Kaplinghat, Ren, HBY (2020)

Fitts+(2018)

Observations: for a given stellar disk mass, the scale radius of the disk varies by a factor of ~10

Simulations: the correlation is much tighter

Milky Way Satellite Galaxies



Missing Satellites, Too Big To Fail, diverse density of the satellite galaxies, anti-correlation between pericenter and central density; Baryon physics (tidal stripping, feedback, star formation history); New physics (SIDM core collapse, Fuzzy dark matter)?

Galactic tides and the Crater II dwarf spheroidal: a challenge to LCDM?

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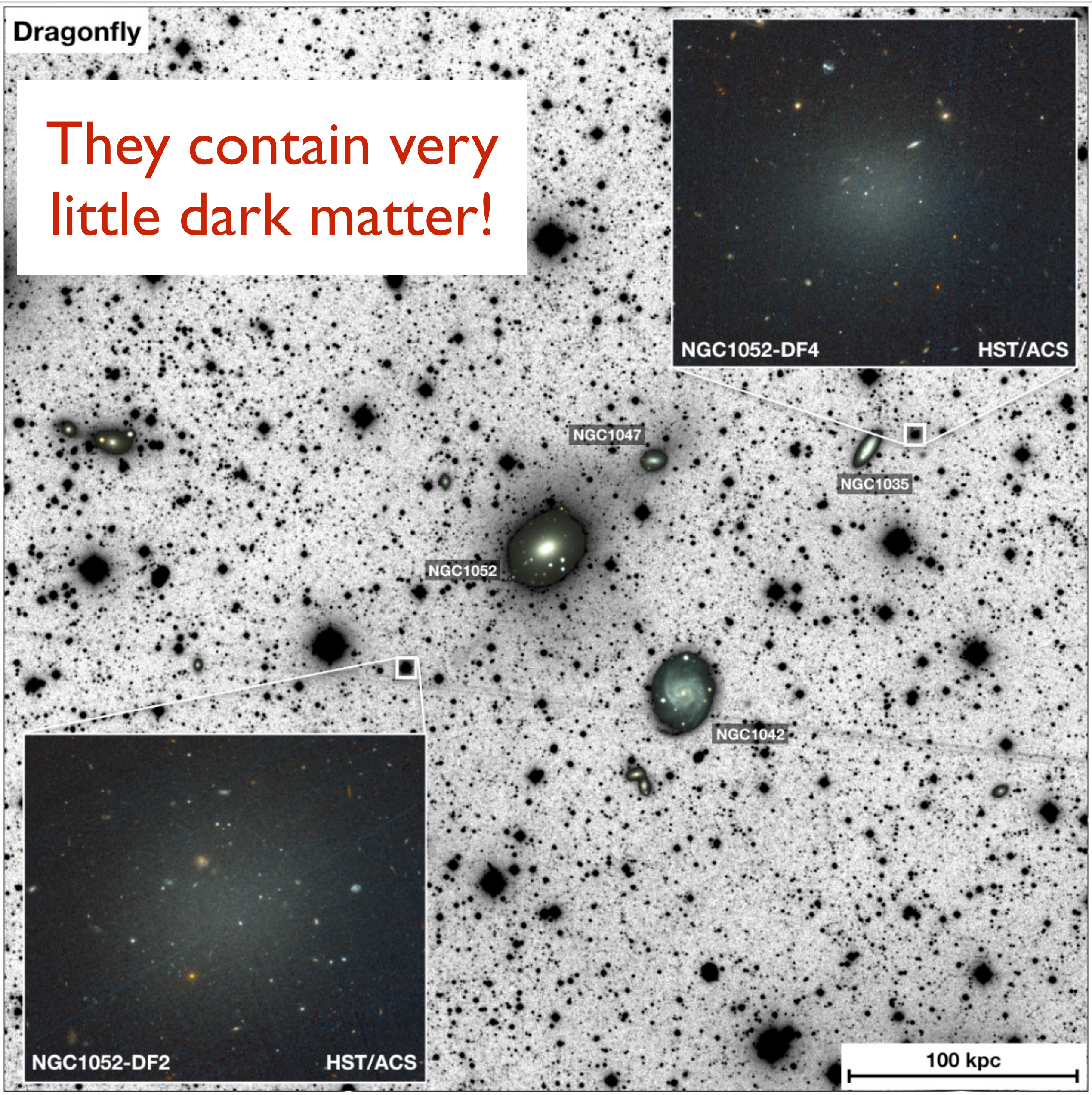
ABSTRACT

The unusually low velocity dispersion and large size of Crater II pose a challenge to our understanding of dwarf galaxies in the Lambda Cold Dark Matter (LCDM) cosmogony. The low velocity dispersion suggests either a dark halo mass much lower than the minimum expected from hydrogen cooling limit arguments, or one that is in the late stages of extreme tidal stripping. The tidal interpretation has been favoured in recent work and is supported by the small pericentric distances consistent with available kinematic estimates. We use *N*-body simulations to examine this interpretation in detail, assuming a Navarro-Frenk-White (NFW) profile for Crater II's progenitor halo. Our main finding is that, although the low velocity dispersion can indeed result from the effect of tides, the large size of Crater II is inconsistent with this hypothesis. This is because galaxies stripped to match the observed velocity dispersion are also reduced to sizes much smaller than the observed half-light radius of Crater II. Unless its size has been substantially overestimated, reconciling this system with LCDM requires that either (i) it is not bound and near equilibrium (unlikely, given its crossing time is shorter than the time elapsed since pericentre), or that (ii) its progenitor halo deviates from the assumed NFW profile. The latter alternative may signal that baryons can affect the inner halo cusp even in extremely faint dwarfs or, more intriguingly, may signal effects associated with the intimate nature of the dark matter, such as finite self-interactions, or other such deviations from the canonical LCDM paradigm.

Key words: dark matter – galaxies: dwarf – galaxies: evolution

We need precision measurements of tidal orbital parameters, stellar kinematics and stellar distributions, and they become available now!

Newly-Discovered Ultra-Diffuse Galaxies



Dragonfly team, van Dokkum+ (2018, 2019)

Milky Way

$$M_{\rm DM}/M_{\rm star} \approx 30$$

DF2 and DF4

$$M_{\rm star} \approx 10^8\ {\rm M}_\odot$$

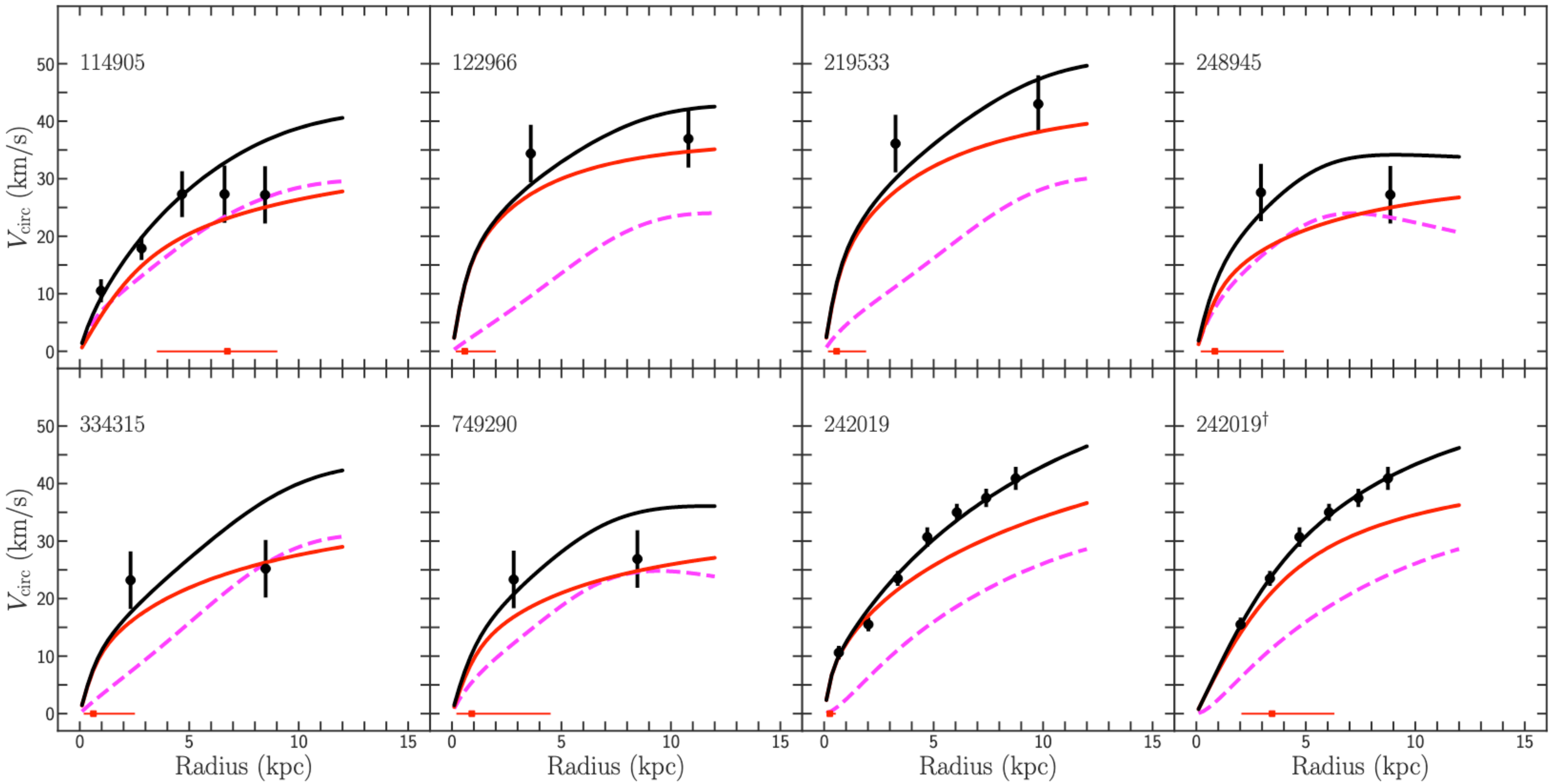
Expected

$$M_{\rm DM}/M_{\rm star} \sim 200$$

Observed

$$M_{\rm DM}/M_{\rm star} \lesssim 1$$

Ultra-diffuse Galaxies in the Field

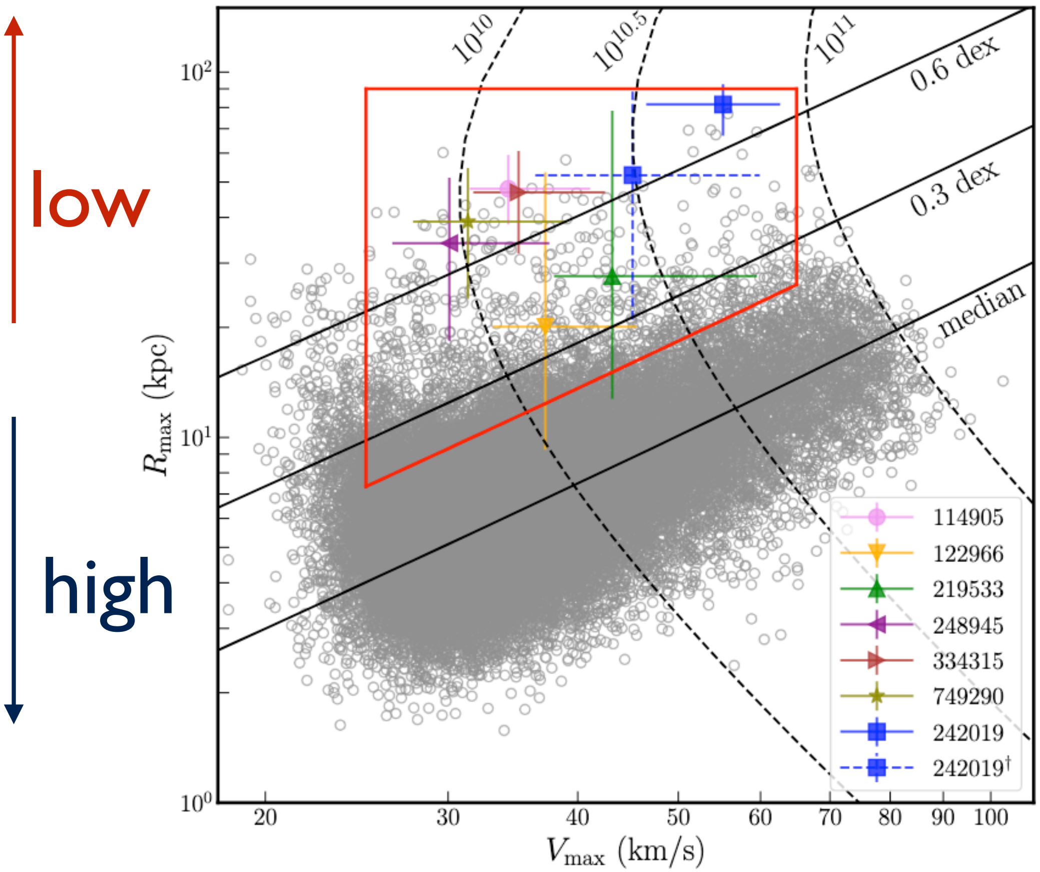


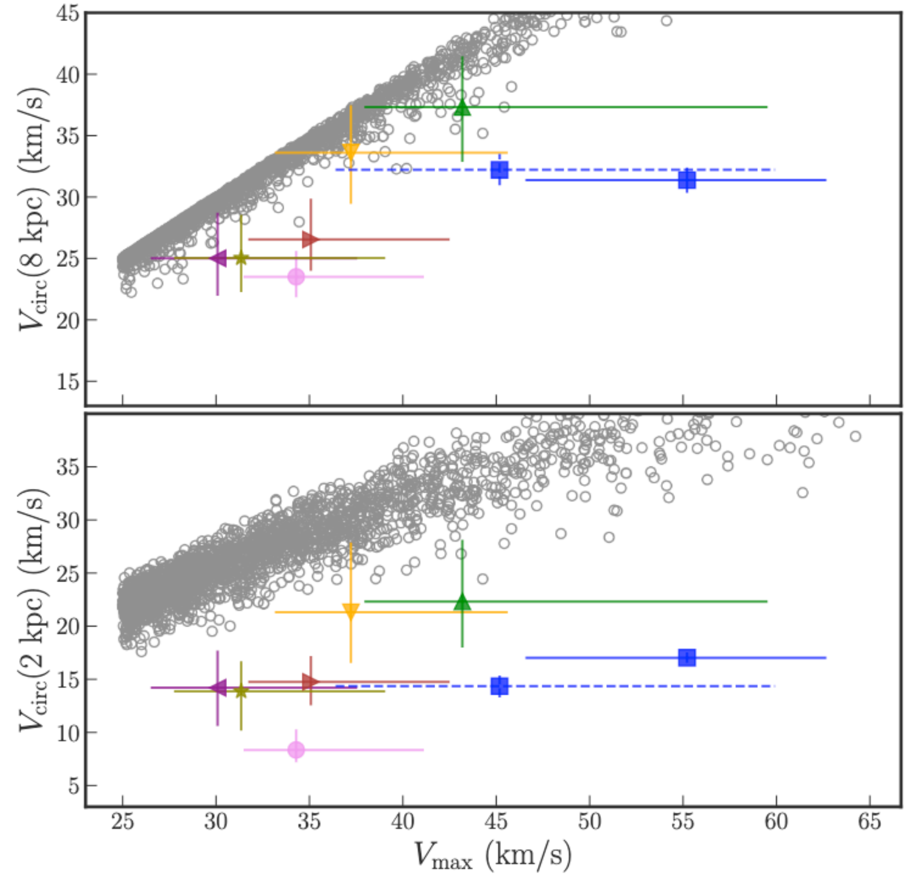
The mechanism of tidal stripping does not apply to the isolated galaxies in the field

Kong, Kaplinghat, HBY, Fraternali, Mancera Pina (2022)

Based on the kinematics data in Mancera Pina+ (2020, 2022) and Shi+(2020)

"Low-Concentration" Halos





- The gas-rich UDGs strongly favor low-concentration halos, "~5σ" lower than the median; this result is robust to the choice of halo density profiles
- These "low-concentration" halos can be found in the the IllustrisTNG dark matter-only simulations (gray); but the inner densities of the simulated halos are too high
- Difficult for feedback to produce the UDG halos

Detection of a Dark Substructure through Gravitational Imaging

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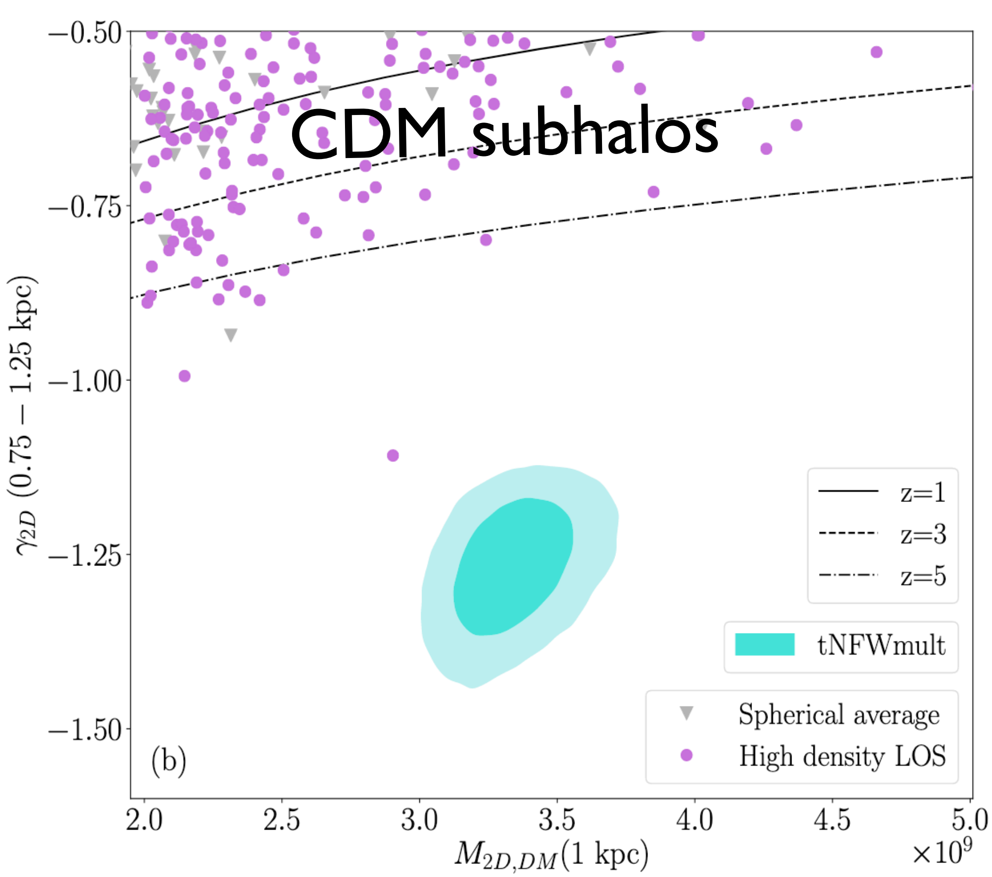
[4] *Institut d'Astrophysique de Paris, CNRS, UMR 7095, Universite Pierre et Marie Curie, 98bis Bd Arago, 75014 Paris, France*

(2010)

SDSSJ0946+1006 (the "Double Einstein Ring").



Minor, Kaplinghat, Vegetti (2020)

- The substructure is extremely dense
- CDM subhalos are not dense enough
- Compared to the IllustrisTNG simulations, the tension with CDM is at the > 99% confidence level
- The substructure does not have a detectable luminous component; baryons cannot help

Opposite extremes:
the UDGs and cored spirals vs the substructure

Gravitational detection of a low-mass dark satellite galaxy at cosmological distance

JVAS B1938+666

S. Vegetti, D. J. Lagattuta, J. P. McKean, M. W. Auger, C. D. Fassnacht & L. V. E. Koopmans

Nature **481**, 341–343 (2012) | Cite this article

Probing Dark Matter with Strong Gravitational Lensing through an Effective Density Slope

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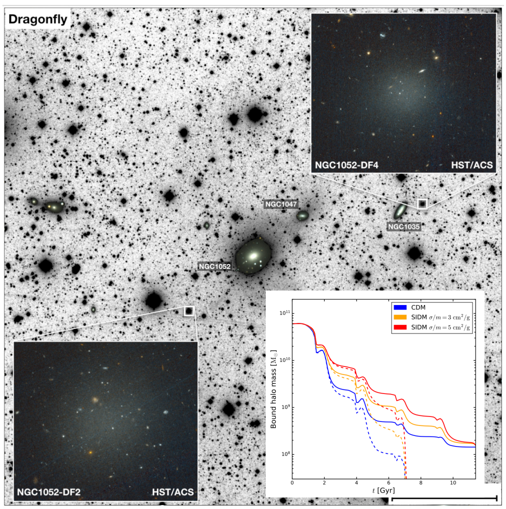
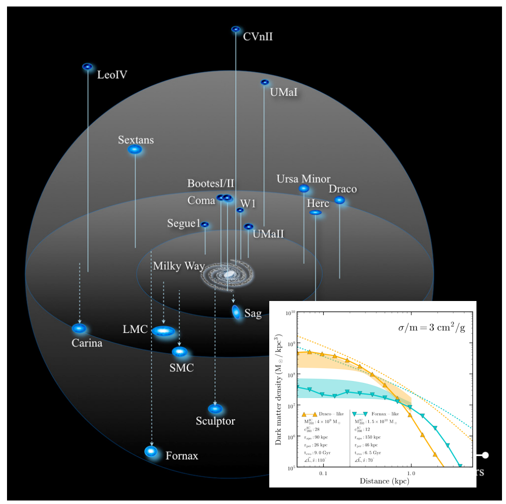
9 August 2022

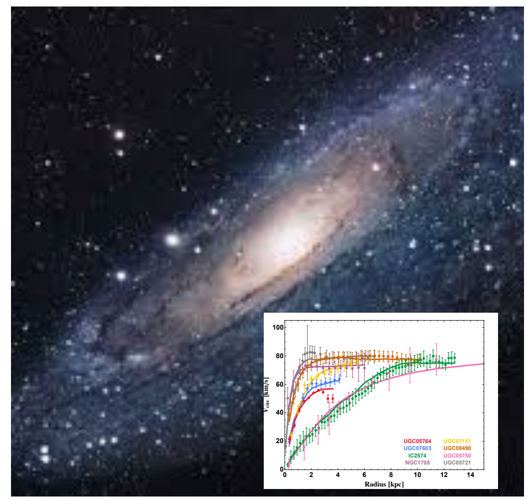
“ between different models. We also present our measurement of the effective density slope $\gamma = 1.96^{+0.12}_{-0.12}$ for the perturber in JVAS B1938+666, which is a 2σ outlier of the cold dark matter scenario. More measurements of this kind are needed to draw robust conclusions about the nature of dark matter. ”

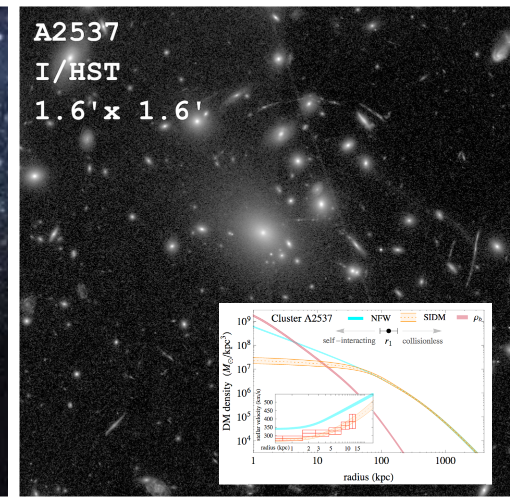
Dark Matter Distributions

Ultra-diffuse galaxies (dark-matter-deficient)	Milky Way satellites	Spiral galaxies	Galaxy clusters





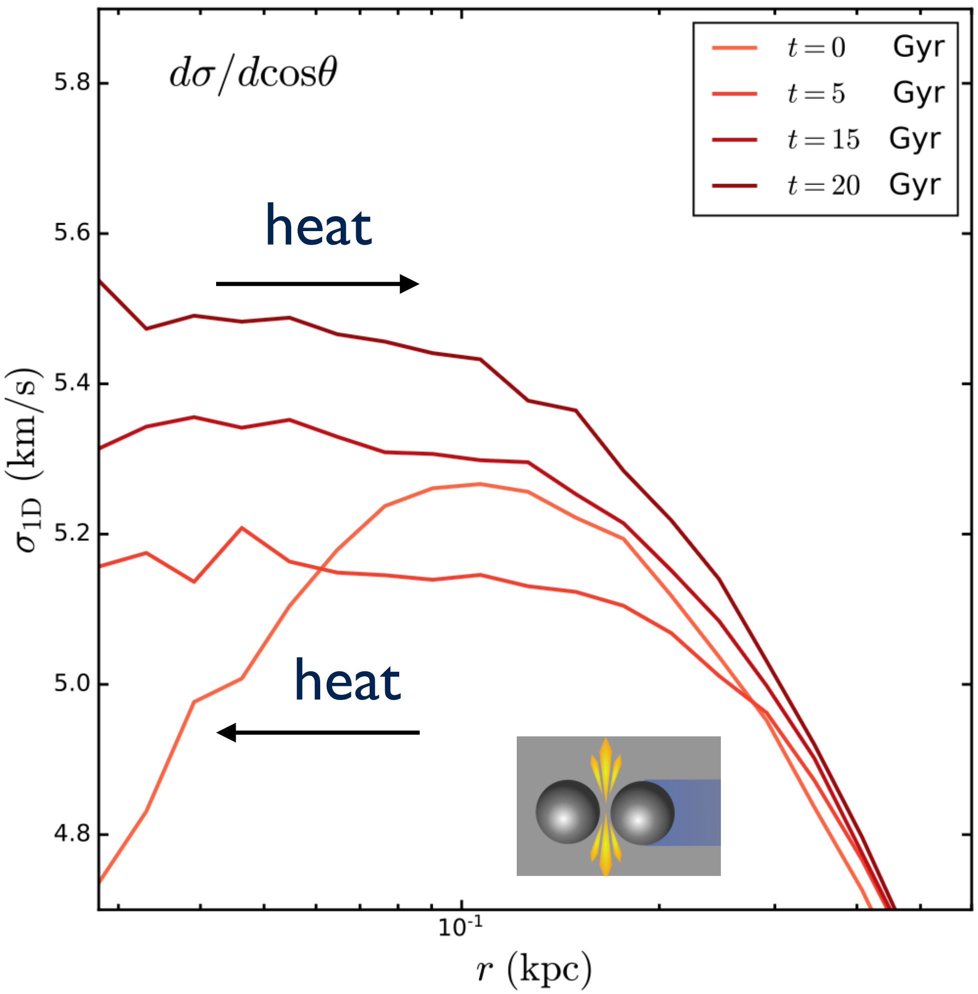


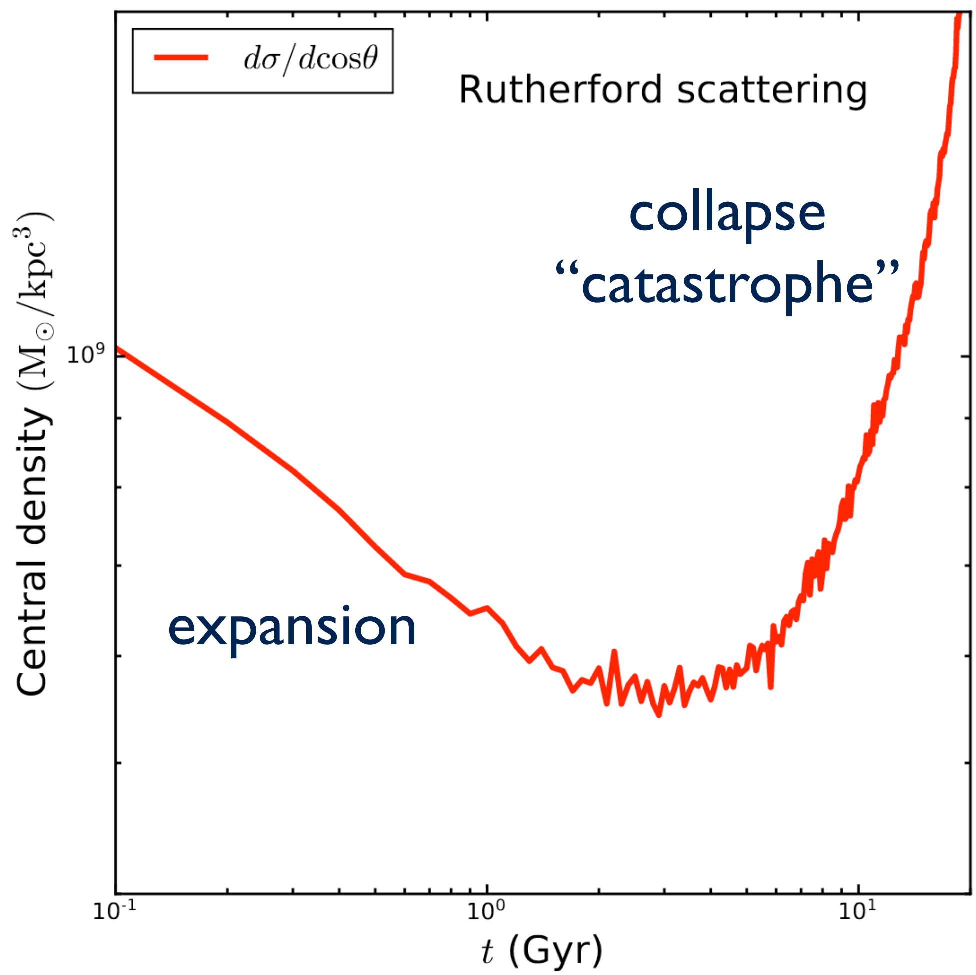


$M_{halo} \sim 10^{8\text{-}10}\ M_\odot$ | $M_{halo} \sim 10^{8}\ M_\odot$ | $M_{halo} \sim 10^{9}\text{-}10^{13}\ M_\odot$ | $M_{halo} \sim 10^{15}\ M_\odot$

- Dark matter distributions are diverse over a wide range of galactic systems
- Baryon physics? New DM physics? Both?

SIDM Gravothermal Evolution





$$2K.E. + P.E. = 0$$

$$E_{tot} = -K.E.$$

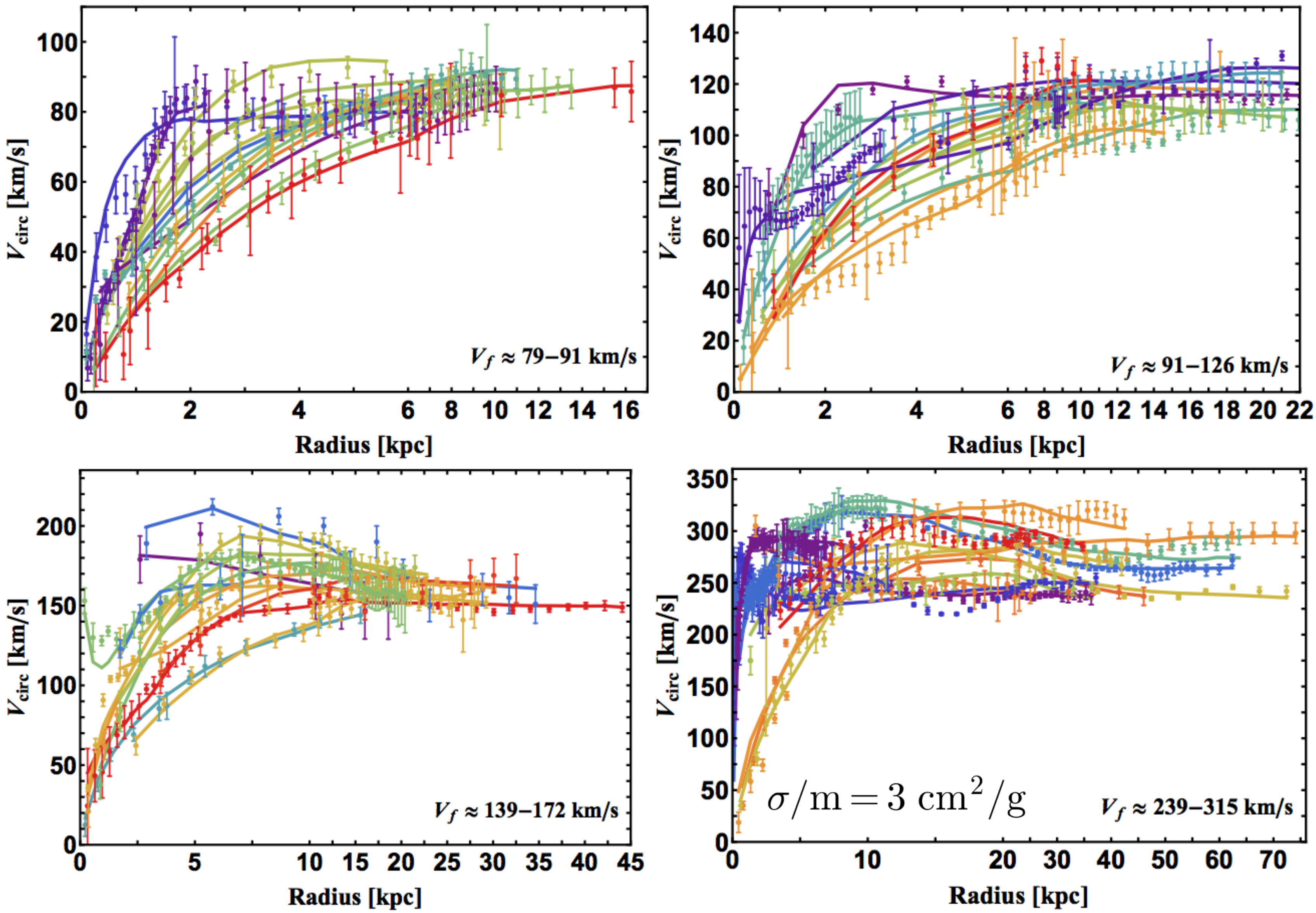
$$\frac{E_{tot}}{T} < 0$$

Negative heat capacity!
⇒ gravothermal collapse

$$t_c \propto (\sigma/m)^{-1} M_{200}^{-1/3} c_{200}^{-7/2}$$

σ/m ~>1-10 cm²/g (nuclear scales)

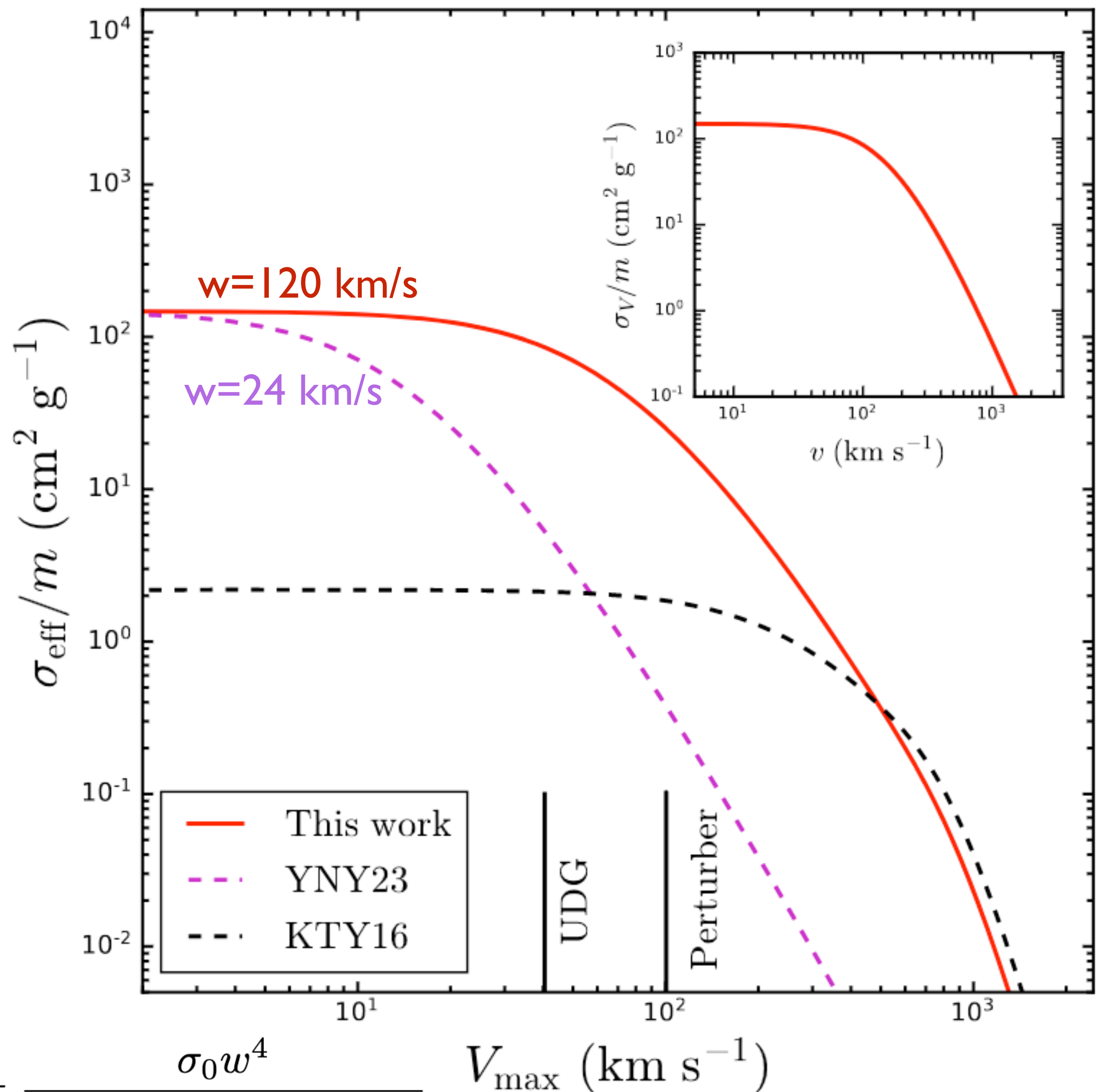
Addressing the Diversity Problem



The solid curves are from the SIDM model (core expansion)

Ren, Kwa, Kaplinghat, HBY (2018)

Even Stronger SIDM

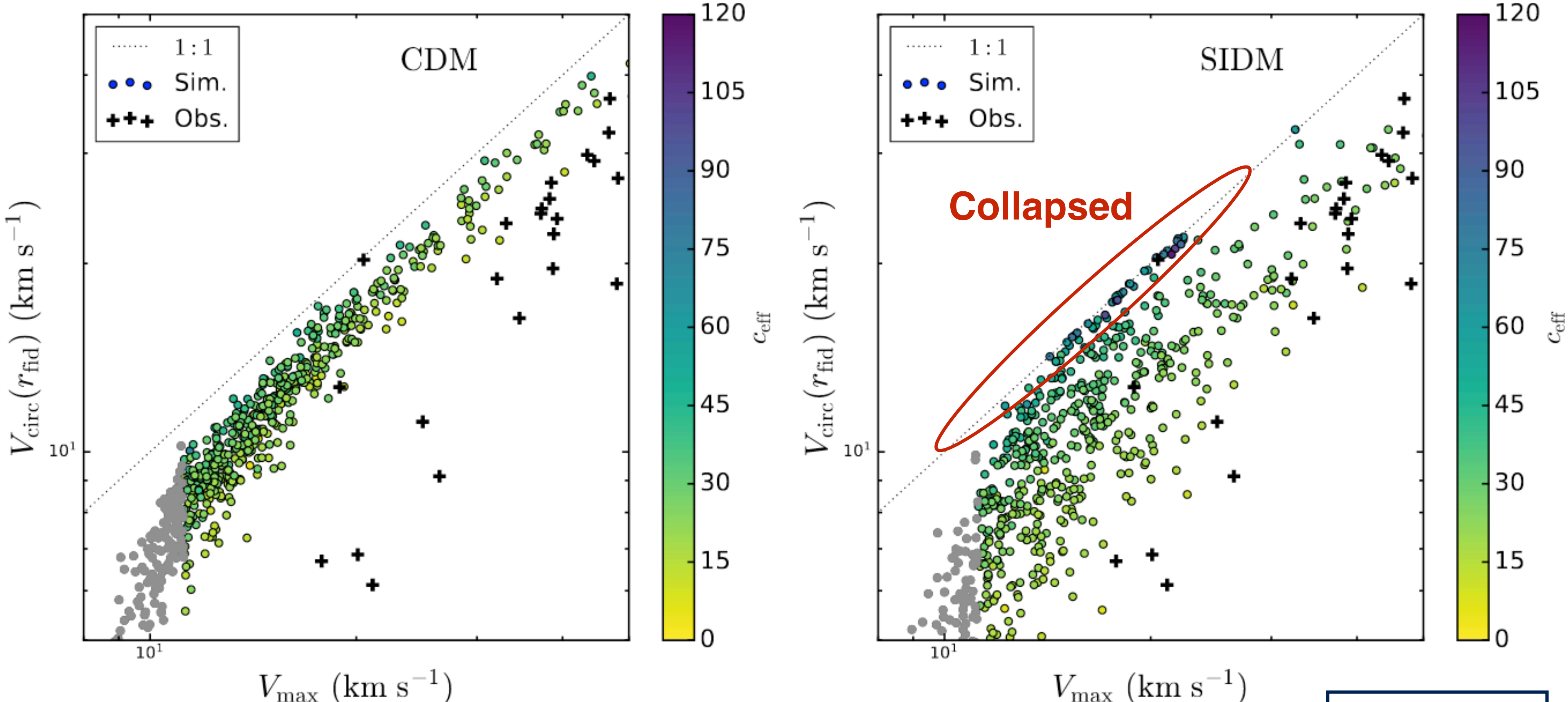


Magenta: MW scale
Yang, Nadler, HBY(2023)
Red: Group scale
Nadler, Yang, HBY (2023)

$$\frac{d\sigma}{d\cos\theta} = \frac{\sigma_0 w^4}{2\left[w^2 + v^2 \sin^2(\theta/2)\right]^2}$$

Even Larger Diversity

Isolated halos | Isolated halos



MW scale

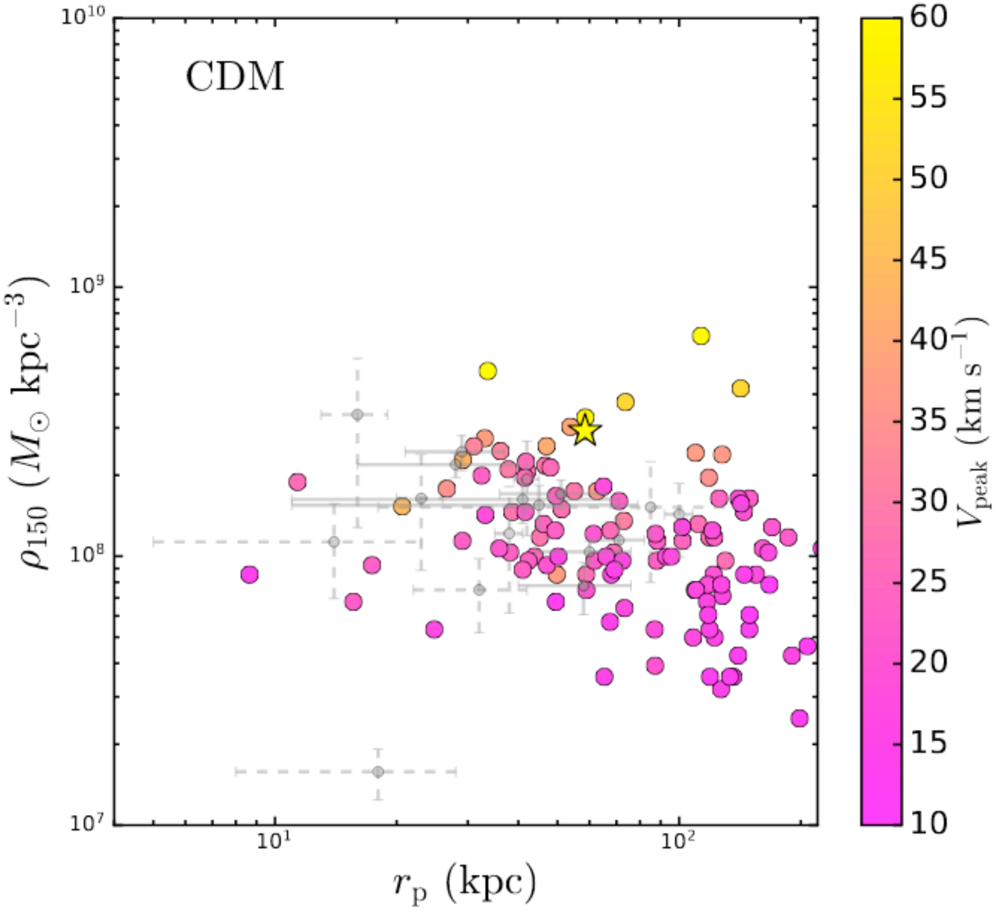
$$V_{\rm circ}(r_{\rm fid}) = \sqrt{\frac{GM(r < r_{\rm fid})}{r_{\rm fid}}} \qquad r_{\rm fid} \equiv 2V_{\rm max}/(70\ {\rm km/s})\ {\rm kpc}$$

- Stronger dark matter self-interactions produce larger diversity
- A constant cross section ~3 cm^2/g is conservative

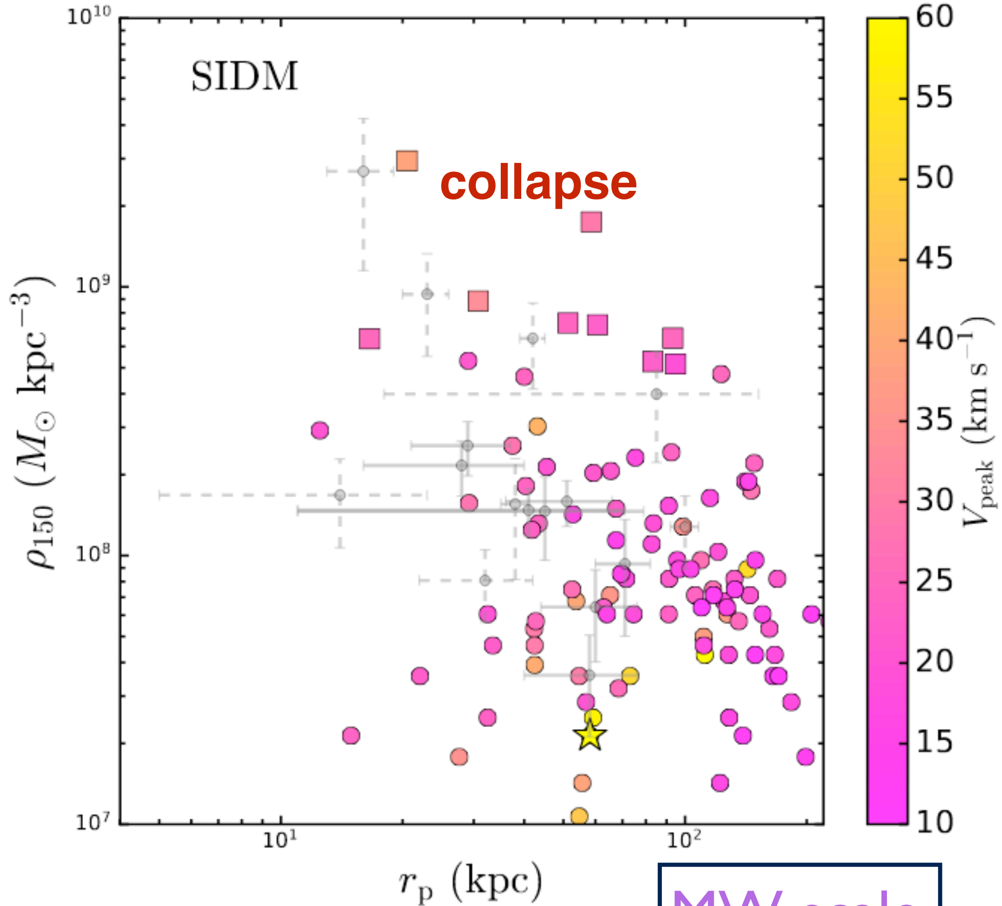
See also Correa+(2022)

Central Density vs Pericenter

Subhalos



Subhalos

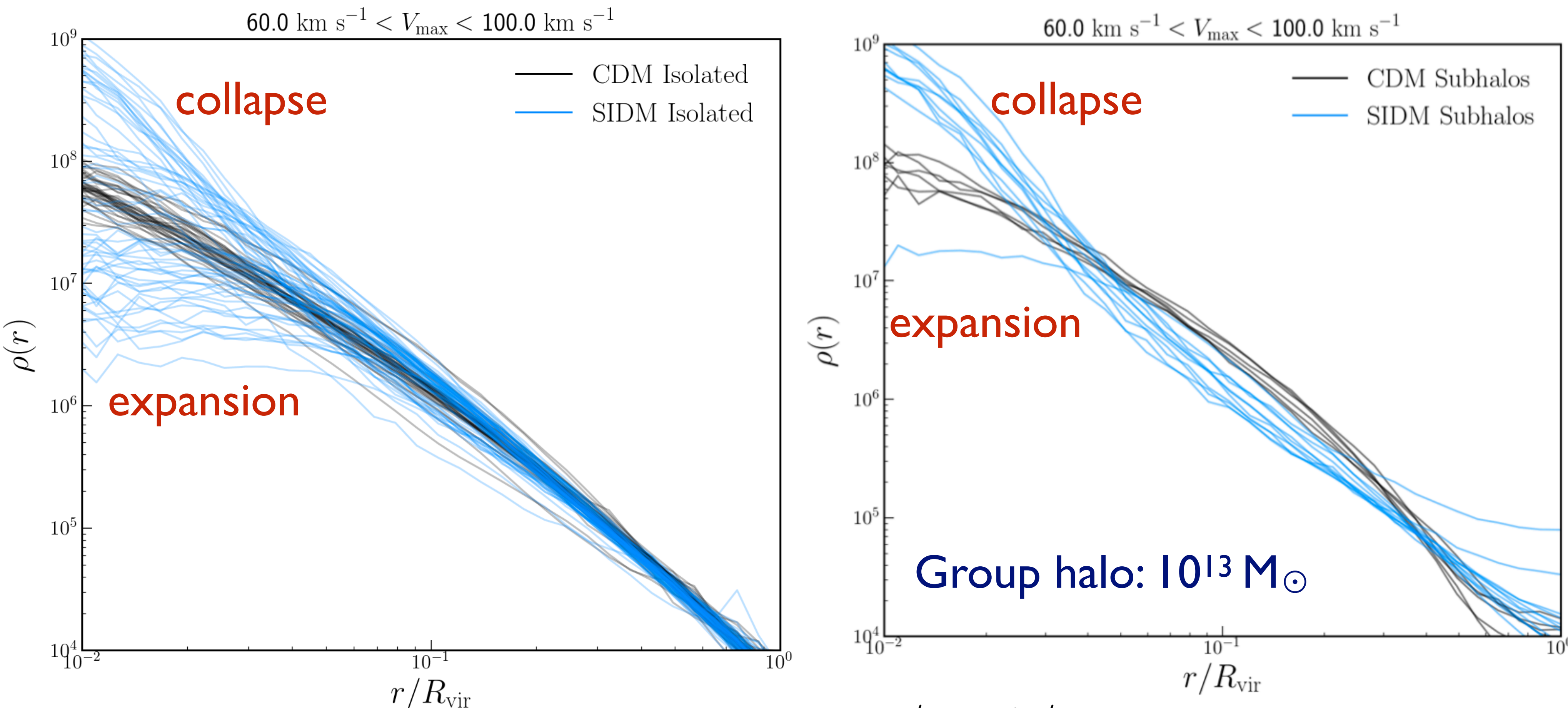


MW scale

- Strong dark matter self-interactions increase the spread and amplify anti-correlation
- For the most ~15 massive subhalos, the CDM simulation does not show the anti-correlation trend
- The stellar disk would "destroy" the subhalos near the bottom

For the discussion on the anti-correlation, see Kaplinghat+(2019)

SIDM Isolated Halos and Subhalos

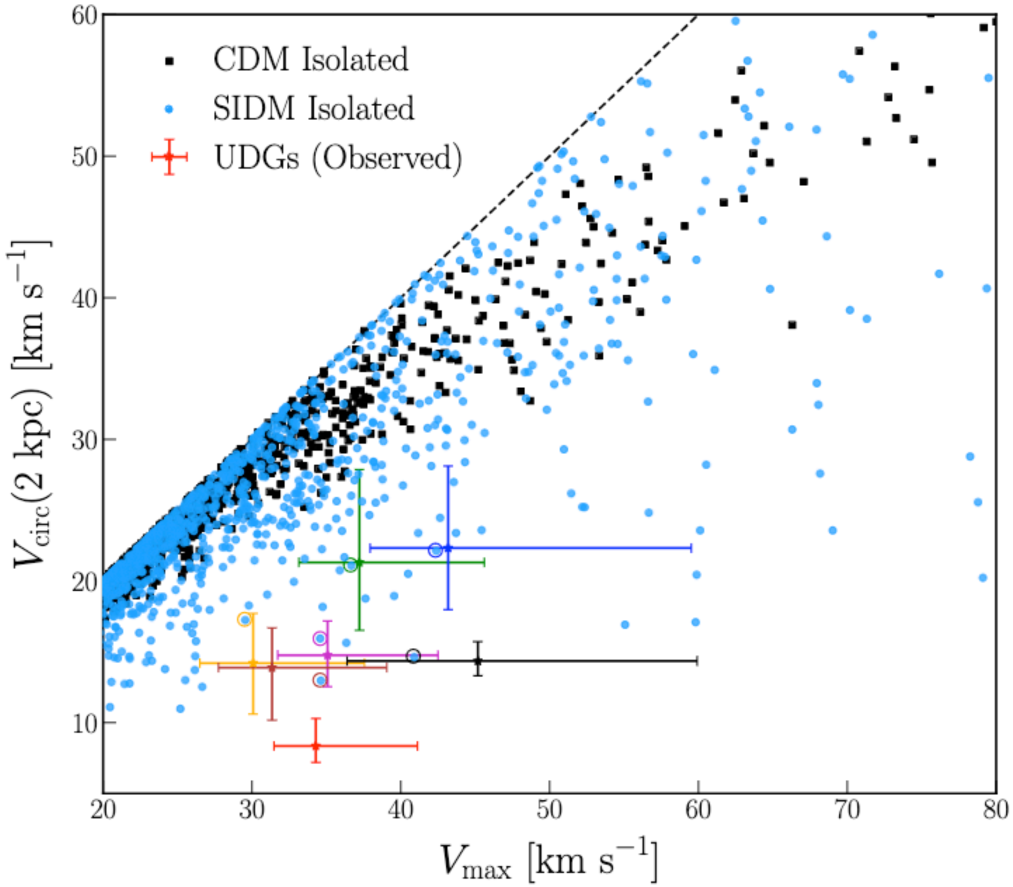


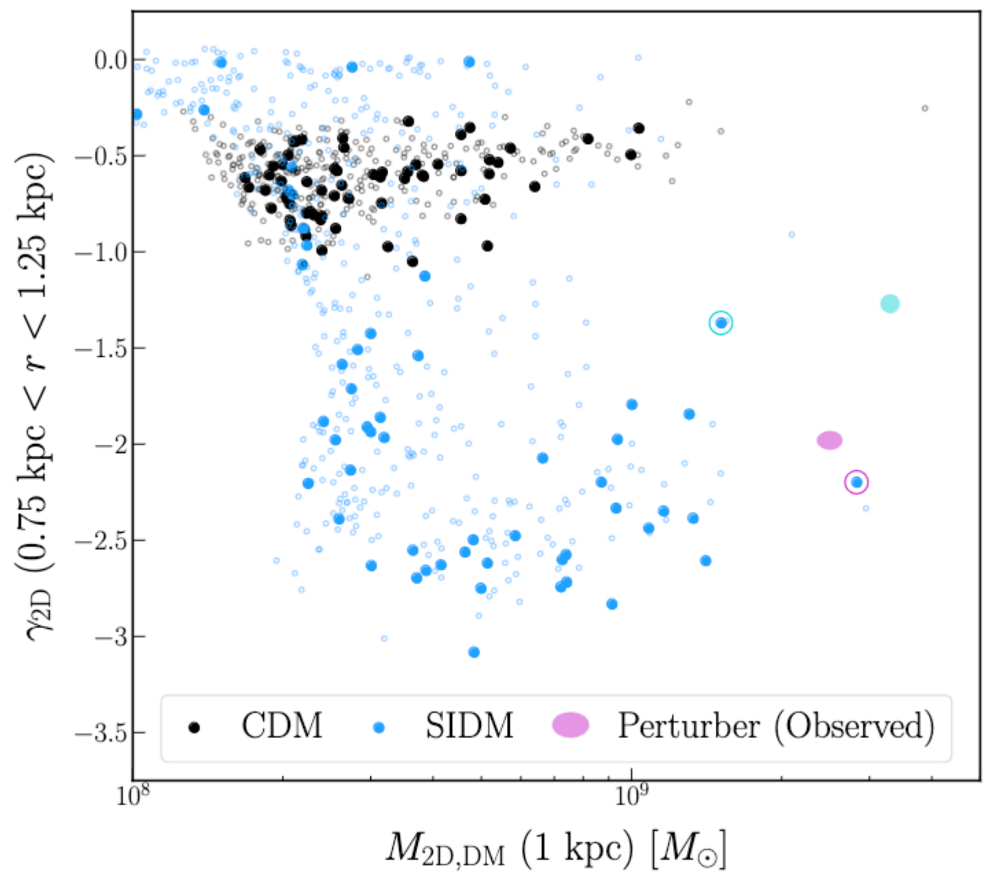
$$t_c \propto (\sigma/m)^{-1} M_{200}^{-1/3} c_{200}^{-7/2}$$

Group scale

- Strong dark matter self-interactions can greatly diversify the inner halo density, due to core expansion and collapse
- Amplify the scatter in the concentration-mass relation

Reconciling UDGs & Lens Perturber

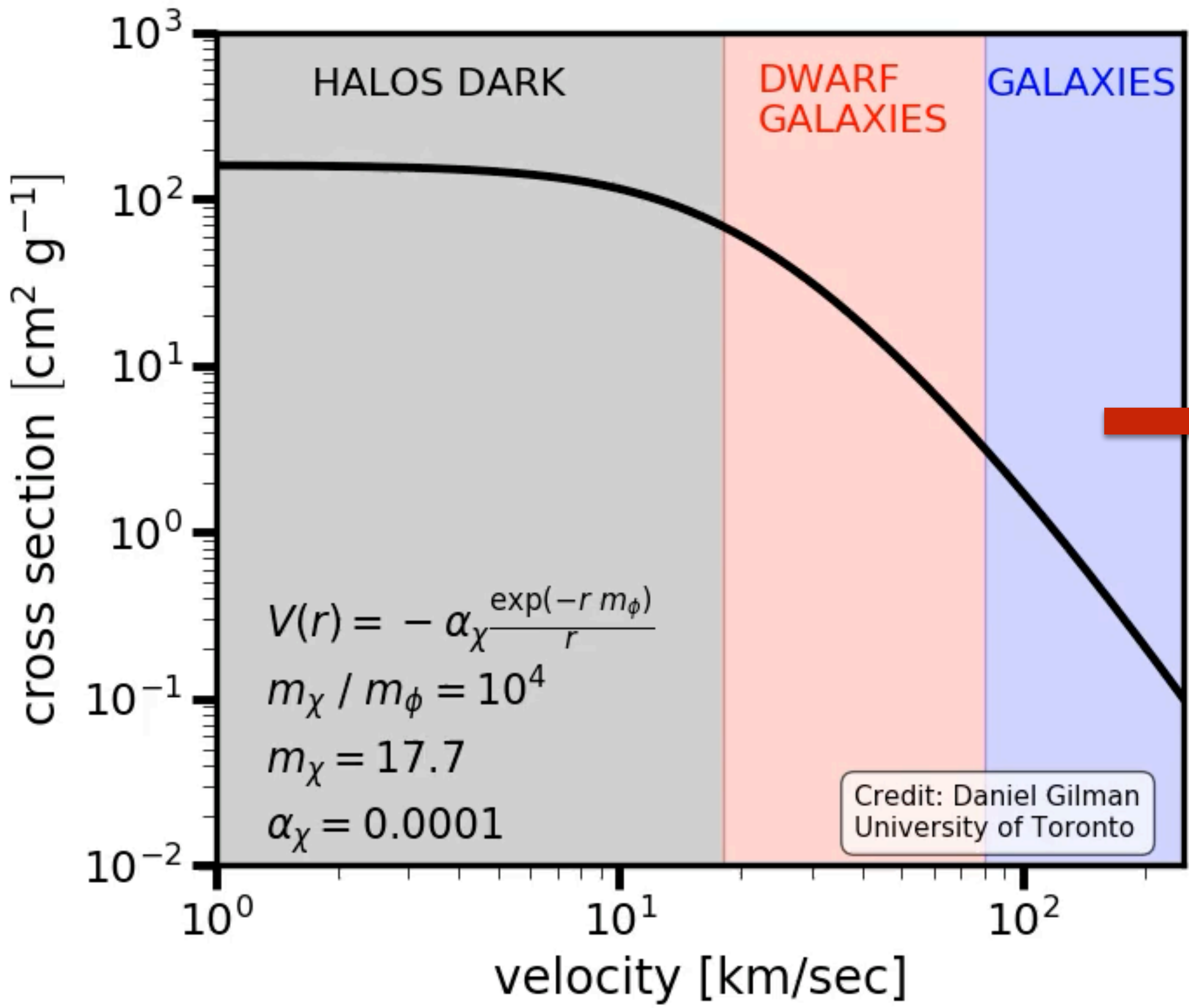




Group scale

There is a slight offset in mass, as the main halo mass is $10^{13}\ M_\odot$ on the lower end of the favored range ~10^{13}-$6\times10^{13}\ M_\odot$; see Minor+(2020)

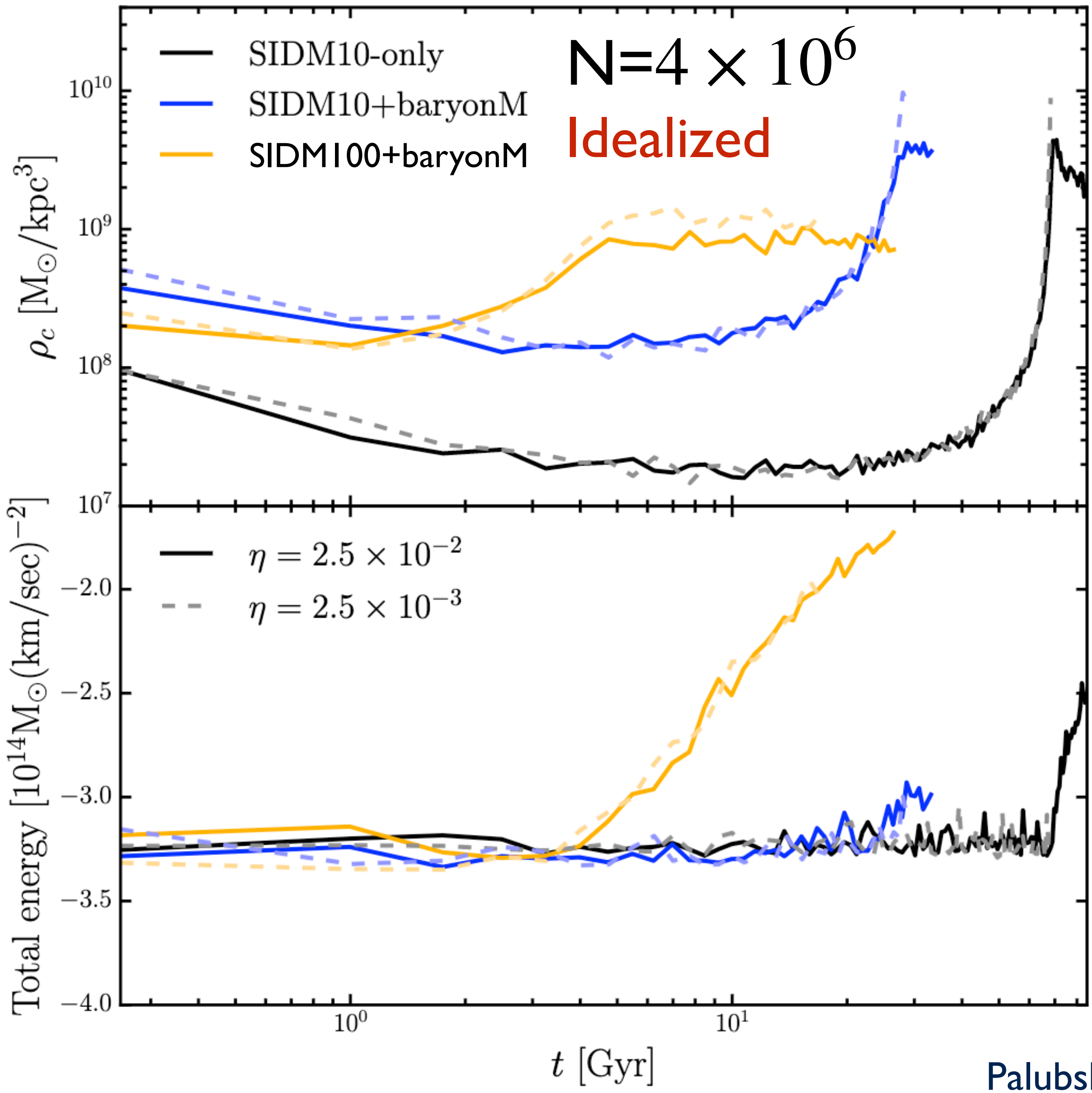
Challenge/OPP: Particle Physics Modeling



Astrophysical Observables

SU(N) dark sectors; production mechanisms; cosmology of dark sectors

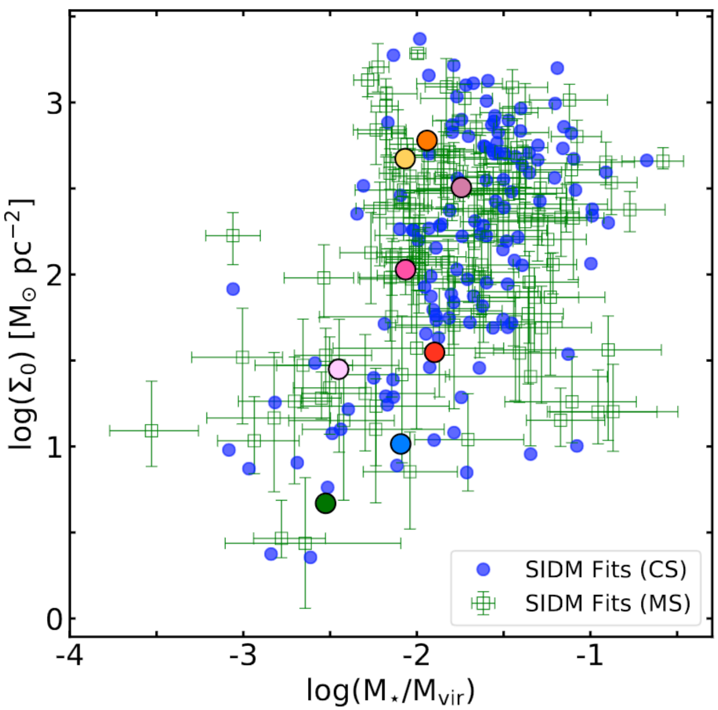
Challenge/OPP: Simulating Core Collapse

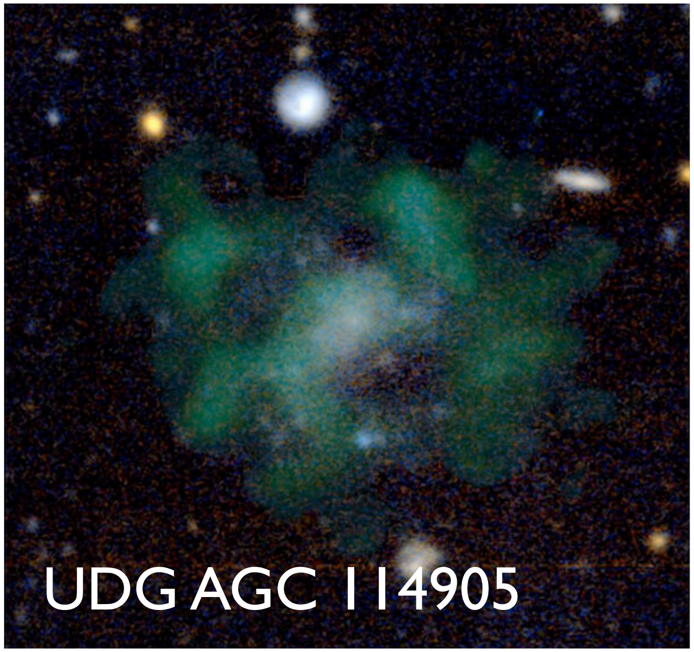


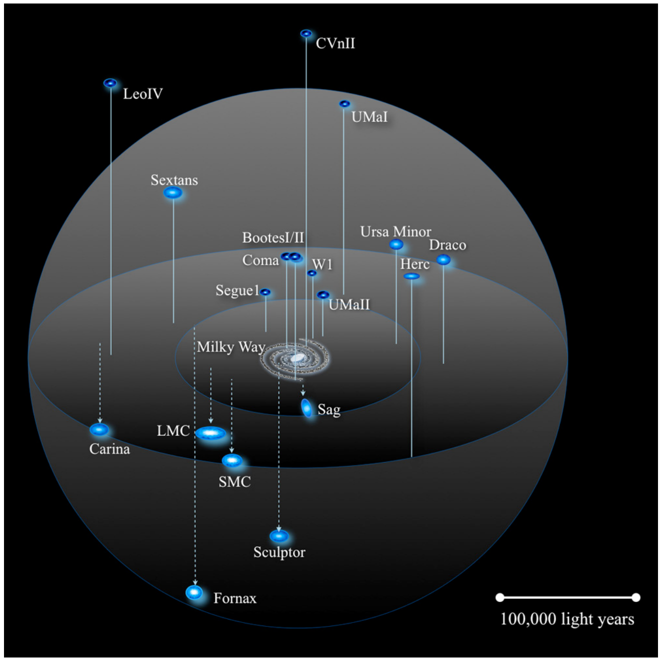
Zhong, Yang, HBY (2023)

Palubski, Kaplinghat (to appear)

Challenge/OPP: Galaxy Formation in SIDM







- Produce a large spread in the size-mass relation for spiral galaxies?
- Explain the formation of gas-rich UGDs in the field naturally?
- Reproduce tidal orbital parameters, stellar kinematics and stellar distributions of the MW satellite galaxies?
- Other novel aspects of galaxy formation and evolution

The workshop program

- Two weeks
- 54 participants, a good mix of grad students, postdocs, and faculty, from different fields, including particle physics and astrophysics (N-body simulations, semi-analytical modeling, observations, galaxy formation, strong lensing)
- Everyone is invited to give a research talk
- We have a working overleaf document; everyone is welcome to contribute; we will submit it to arXiv (journal as well?)

Moderated discussions
06/20: SIDM particle physics models
06/21: Milky Way and dwarf galaxy constraints
06/23: SIDM simulations and semi-analytical modelling
06/27: Rotation curves, Milky Way Satellites
06/28: Strong Lensing

We need volunteers as moderators and scribes
(at least two volunteers for each discussion session)